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January 4, 2017

# LBNF/DUNE Flux Spectrometer Concept

This document is a response to a formal request for information by Mark Thomson on November 1 2016. In coming up with answers, we gratefully acknowledge very informative and useful inputs from Phil Adamson, Sam Childress, Cory Crowley, Jim Hylen, Vaia Papadimitriou, Matt Quinn, Diane Reitzner and Salman Tariq.

## Introduction

The LBNF/DUNE Flux spectrometer concept is a proposal to measure the muon and hadron flux after the LBNF focusing horns and before the decay pipe. A strawman design for the spectrometer is shown in Figure 1. There are two possible locations for the apparatus – inside the LBNF target chase in a very low-intensity configuration of LBNF (in situ), or in an external beamline at Fermilab (ex situ). The goal is for spectrometer to measure the absolute neutrino parent flux after the focusing horns to an accuracy of 1 to 2%.

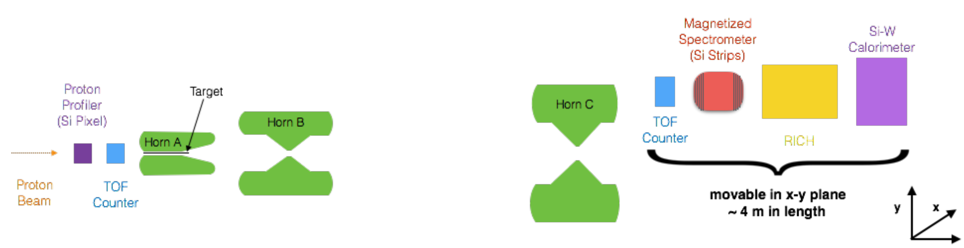


Figure 1: Schematic of one possible configuration of the spectrometer. Not to scale.

## Do the DUNE physics goals require the spectrometer? This question should be addressed with a preliminary assessment of the impact on the overall sensitivity.

Existing long-baseline oscillation experiments have relied largely on the Near Detector to limit the impact of large flux uncertainties. In this flux times cross section paradigm, detailed knowledge of the neutrino beam and neutrino scattering cross-sections are not required, as oscillation parameters are estimated by comparing event rates in the far detector to predictions extrapolated from the Near Detector before the beam has oscillated. While this has been sufficient for statistically limited experiments, it may lead to serious mistakes as neutrino oscillation measurements push to higher precision. One reason for this is that the composition of the neutrino flux depends on the geometry of the beam and detectors. The Near Detector sees a broad cross section of the beam, while the far detector sees only a very narrow solid angle. Thus, the neutrino flux for a given flavor is different at the Near and Far Detectors, as shown in Figure 2.

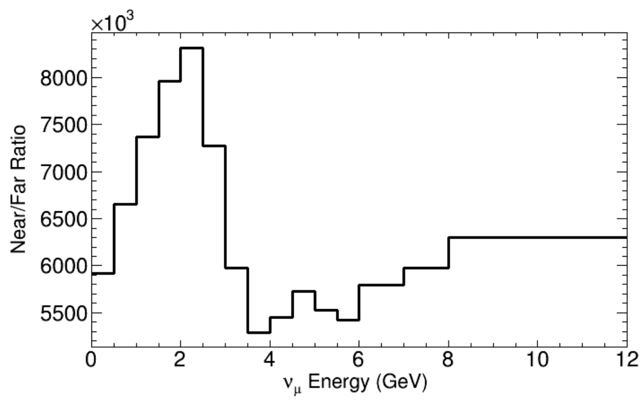


Figure 2: Ratio of fluxes at the near and far detectors, estimated using g4lbnf configured to simulate the two-horn optimized design described in [1]

To quantify the neutrinos fluxes and their uncertainties, one currently has to rely on sophisticated Monte Carlo simulations to compute the flux of neutrino progenitors. While decays of pions, kaons and muons are well known, there are substantial uncertainties in the number of these particles produced in the beamline, arising from numerous unknown hadro-production, elastic, and quasi-elastic cross-sections. Estimates of the uncertainty on the DUNE $\nu_\mu$ flux using the multi-universe statistical method developed by the MINER$\nu$A experiment are approximately 8% in the focusing peak [2], with uncertainties on the near/far flux ratio of 1-2% – see Figure 3.

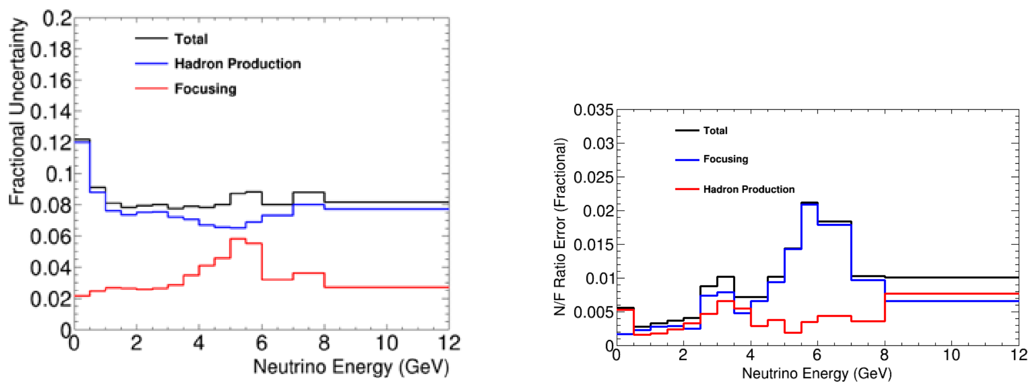


Figure 3: Estimated uncertainties on the neutrino flux at the DUNE far detector (left) and on the ratio between the near and far detectors (right), assuming the 2-horn optimized design described in [1].

Although this is the most advanced procedure available for estimating flux uncertainties, it relies on guesses to how wrong models of unmeasured differential hadro production and elastic scattering cross sections may be. It also does not take into account the possibility of substantial mistakes in the beam simulation which could cause inaccuracies at the level of tens of percent. Issues such as overly simplified horn shape models, ommisions of cooling water, and unsimulated shifts in the horn positions have been recently discovered in the NuMI beam simulation. DUNE should be prepared for the possibility of similar problems. The 1-2% precision of the flux spectromter concept would be a substantial improvement over the current uncertainty estimate of 8%. Moreover, it would correct many of the potential simulation inaccuracies that are not accounted for in this estimate.

The impact of the spectrometer measurement on the overall DUNE sensitivities is difficult to determine at this time, as it requires a complete and detailed simulation of the analysis. The only tool for estimating sensitivities available at the time of this writing is the GLoBES configuration used for figures in the DUNE CDR, such as those shown in Figure 4. These show the projected sensitivity of the experiment to CP violation and the mass hierarchy as a

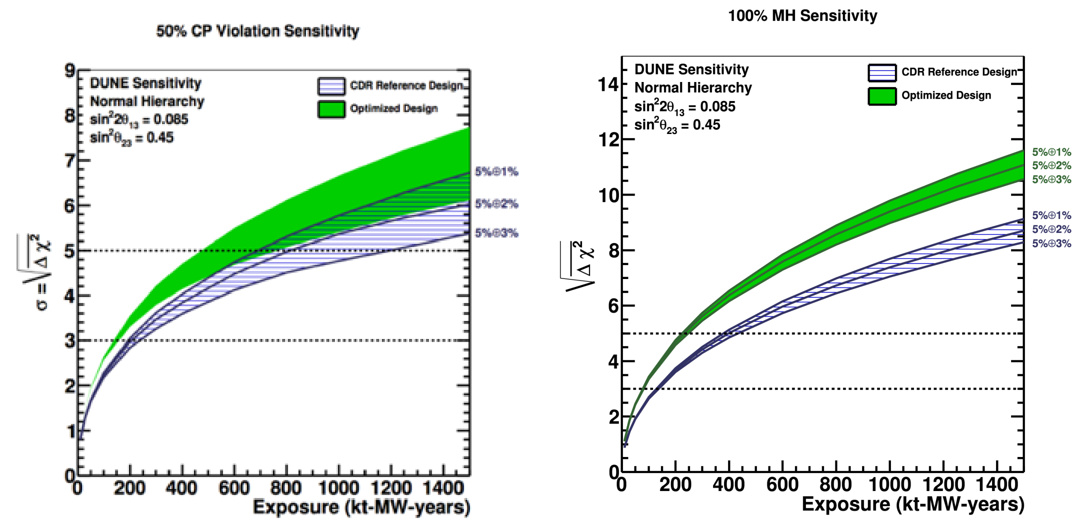


Figure 4: Projected DUNE sensitivities to CP violation (left) and the mass hierarchy (right) given two different beam options and several different systematics scenarios: in all cases a (5%) normalization uncertainty on the $\nu_\mu$ spectrum at the far detector, correlated with the $\nu_e$ signal spectrum is assumed. The width of the bands shows changes in sensitivity when the additional normalization on the $\nu_e$ signal, uncorrelated with $\nu_\mu$, is varied between 1% and 3%.

function of exposure for two different beam options and for several systematics scenarios. A setup similar to that used for the CDR has also been used to study the impact of systematics on precision measures of oscillation parameters such as $\Theta_{13}$ (see Figure 5).

These studies indicate that DUNE's physics reach will be strongly controlled by the experiment's ability to control the uncertainty on the $\nu_e$ appearance spectrum that is uncorrelated with the $\nu_\mu$ spectrum. Since both the $\nu_\mu$ and oscillated $\nu_e$ spectra at the far detector arise from the same $\nu_\mu$ flux before oscillation, the flux uncertainty does not enter into this critical uncertainty directly. However, the large uncertainties in the unoscillated flux will couple to large uncertainties in the relative cross sections of electron and muon neutrinos.

The GLoBES analyses shown in Figures 4 and 5 involve extremely simplistic treatments of systematic uncertainties. All detector, flux and cross section uncertainties are combined into single normalization uncertainties that is fully correlated across energy. Moreover, shape uncertainties are not considered in these studies; this is a critical omission, since roughly half of DUNE's sensitivity to CP violation will come from observations of spectral shape – see Figure 6, and flux uncertainties are expected to have substantial variations as a function of

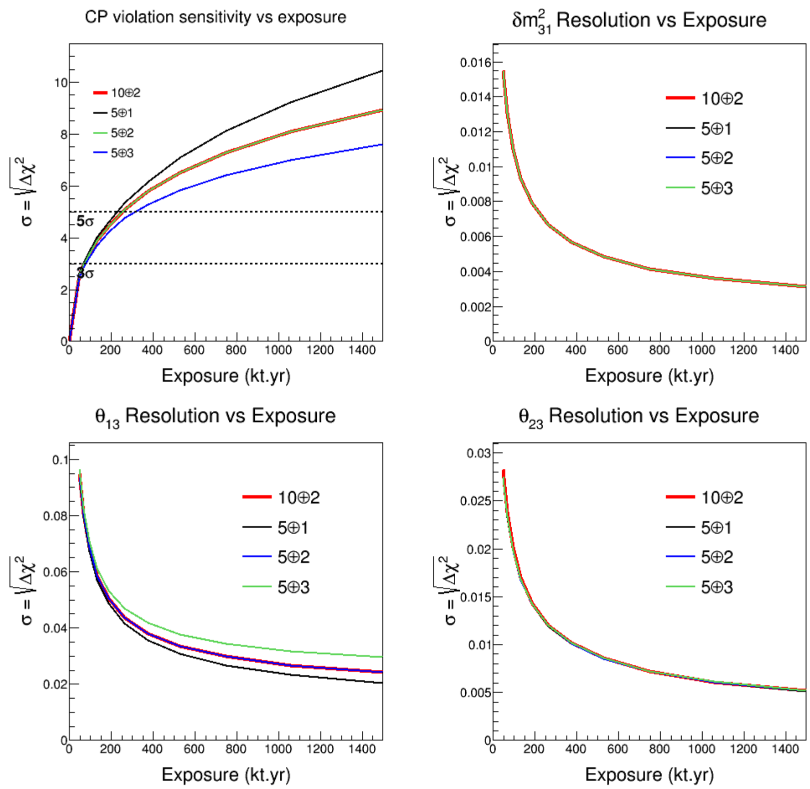


Figure 5: Projected DUNE sensitivity to CP violation for 50% of the values of $\delta_{CP}$ (top left) and fractional resolution of $\delta m^2_{31}$ (top right), $\theta_{13}$ (bottom left), and $\theta_{23}$ (bottom right) as a function of exposure assuming an optimized beam and several systematics scenarios. The first (second) number in the legend denotes the normalization uncertainty on the $\nu_e$ signal that are correlated (uncorrelated) with the $\nu_\mu$ signal.

energy.

In addition to the long-baseline program, DUNE will conduct a rich program of physics at the near detector, including precision measurements of neutrino interaction cross sections and searches for sterile neutrinos. Both of these measurements would be substantially improved by the flux spectrometer measurement One particular danger for the near detector program is the possibility of an innacurate flux model causing a false signal for a sterile neutrino. This would have a potentially devastating impact on precision measurements in the far detector, which necessarily rely on a 3-flavor oscillation assumption.

In conlusion, while we are hesitant to use the word "required", as DUNE will definitely be able to make measurements in the absense of the spectometer, we believe the spectrometer will substantially improve the value of those measurements. Not only will it improve the pre-

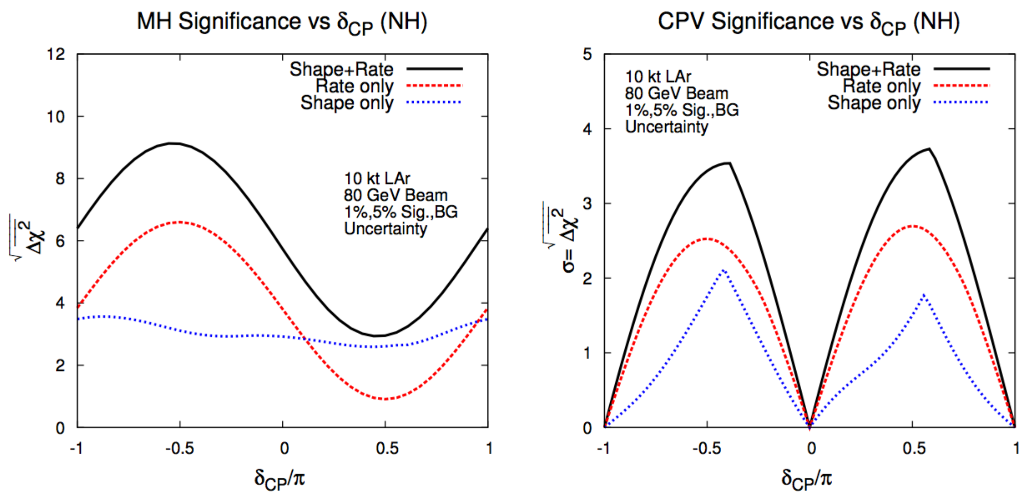


Figure 6: The mass hierarchy (left) and CP violation (right) sensitivities from shape, rate, and shape+rate. The sensitivity is for a 10kt detector, 1.2MW beam, 3+3 ( + ) years, for true normal hierarchy. Reprinted from [3].

cision of essentially all measurements made in the near detector, it will substantially reduce risks associated with DUNE's goals of precision measurements of the PMNS oscillation parameters. Finally, we not that the measurements discussed here are the first goals of a facility that is likely to run for decades. We do not currently know what the facility will be asked to do after DUNE's initial goals are reached, but in essentially any scenario, a measurement of the neutrino fluxes via the spectrometer will be valuable.

## If so, is it required to be installed inside the LBNF target station every time there is a change of target/horn configuration?

In case we do not have an ex situ facility, two distinct sets of circumstances will prompt us to re-install the spectrometer in the chase:

- The replacement of any of the focusing system components (target or horns) may prompt us to measure again the flux. It will be a requirement for any change in the target design (such as a modification of the geometry of the target or a change in materials), or a change in the horns design (such as a modification of the shape/thickness of the inner conductor, or a reconfiguration of the horn positions).

- The observation of an unexpected and significant change of particle flux detected in the muon monitor system (and possibly in the hadron monitor), or a distortion of the neutrino interaction spectrum shape and/or normalization change in the near detector. Such changes may occur, for instance, if a horn goes out of alignment, or if the target degrades, e.g. its density changes.

If we are equipped with an ex situ facility, we may still need some measurement in the target chase to address point 2, since the observations in the muon monitors or the near detector may not be enough to identify the problem. In this case, a simpler tracking plane downstream of the horns just to record the particle flux would be of great help to identify the problem.

## For the two options of installing the spectrometer in situ either after Horn C or between Horn B and C, provide an estimate of the additional costs (spectrometer and CF) and the impact on the operational schedule how much time would be devoted to spectrometer operation and how often.

*Additional Costs*

In order to be able to operate the spectrometer in the LBNF target chase, slow extraction at MI10 is required, such that the instantaneous intensity be of the order of one proton per 53 MHz bucket. The presently installed septa in the Main Injector can provide the right phase advance for beam extraction in the LBNF beamline at MI10. Removable collimators will need to be installed in the LBNF beamline to further reduce the beam intensity by a factor $10^4 - 10^5$. Additional removable instrumentation (BPMs, SWICS), sensitive to the low intensity slow extracted beam, will need to be installed in the LBNF beamline. The cost of these modifications to the LBNF beamline has been estimated to be about $xxM.

The spectrometer has not been fully designed yet. For the in situ option, it will be approximately 4 m long, with an aperture of 5x5 cm$^2$. Tracking will be provided by planes of silicon strip detectors. The cost of spectrometer itself is expected to be dominated by the engineering and technical man power. A rough estimate of the cost is about $5M.

The spectrometer will need its own support module, with a precision alignment mechanism. In addition, a precise positioning table will be required, to move the spectrometer across the full cross section of the horn. The cost has been roughly estimated to be $3.5 M. This takes the $2.34 M cost of the current Horn 1 module, adds $0.2 M for a precision positioning table, and assumes a 30% contingency.

Should the spectrometer be installed downstream of Horn C, the ideal location for it, then we will have to extend the chase by approximately 4.5 m., and to commensurately reduce the length of the decay pipe. Since we do need crane coverage for the spectrometer module and the beam decay pipe window, this means we have to extend the building hosting the chase as well. Note also that a small increase ( 10%) of the radius of the beam window is probably warranted, to maintain the same physical aperture for the neutrino progenitors beam. Thus, the design of this beam window would have to revisited. The cost for installation downstream of Horn C has been roughly estimated to be $12.35 M. Should the spectrometer be installed between Horn B and Horn C, only very basic modifications to the target shield pile would be necessary; a basic cost estimate for those modifications, including a new carriage support system for the spectrometer module, is $0.5 M.

Finally, careful studies of the radiological background coming from the target, the horns, and probably more importantly, the wall of the chase will have to be estimated for an installation in situ. Based on a gamma survey of NuMI Horn1 and MARS/Geant4 simulations, this background was found to be not negligible. While we anticipate using a fine grained tracking detector, more studies of the existing NuMI chase will need to be done to assess the feasibility of a measurement in situ. A high precision germanium detector is required for such studies; the cost of such instrumentation is of the order of tens of thousands of dollar, up to 90k, depending on the ease of use, portability, and DAQ interface capabilities.

*Impact on the operational schedule.*

For the in situ option, we anticipate to be able to install the spectrometer, after a week cooling down period, in a few days, including alignment. We anticipate a running time of 1 week to characterize the flux, followed by a few days for removal of the spectrometer and the installa-

| | In Situ (After Horn C) | In Situ (After Horn B) | Ex Situ |
|---|---|---|---|
| Spectrometer | 5M | 5M | 5 M |
| Spectrometer Module | 3.5 M | 3.5 M | - |
| Removable Colimators | XXX | XXX | - |
| Low Intensity Instrumentation | XXX | XXX | - |
| Chase Modifications | 12.4 M | 0.5 M | - |
| HpGe Detector | 0.1 M | 0.1 M | - |
| Horn Power Supply | - | - | 4.5 M |

Table 1: Summary of costs of the three location options

tion of the top of the chase shielding. During this time neutrino running at LBNF will not be possible. Assuming the the measurement is performed once per year at the end of the yearly maintenance shutdown, it will impact data taking by 6%.[1]

## For the in situ option, the collaboration would like to understand any the potential impact on the overall LBNF schedule.

We do not expect any impact on the LBNF construction schedule, except for a very modest cost increase for the design of the spectrometer support module and positioning table.

## Can the ex situ option provide the necessary constraints? What are the estimated additional systematic uncertainties in transferring the results to the actual beam configuration?

Flux uncertainties arise from two broad categories of sources: models of hadron production off the target and modeling of focusing parameters such as horn positions and currents. The ex situ option would measure the dominant of these two sources, hadroproduction models, while the in situ option would measure both. Uncertainties on the ex situ measurement would therefore be added in quadrature to the focusing uncertainties. Current estimates of focusing uncertainties are 2-5% depending on neutrino energy, and are largest at the falling edge of the focusing peak. Several of the focusing uncertainties, such as the 2% uncertainty

[1] This estimate assumes 276 days of LBNF running per year, 10 days of spectometer installation and extraction, and 7 days of spectrometer running.

on proton counting, can likely be reduced with further study. Moreover, with an ex situ setup, the effect of misalignments could be directly studied, by e.g. shifting horns by small amounts and remeasuring the hadron flux.

Since these uncertainties that are accessible only to the in situ option are not large, the major advantage of the in situ option is that we would measure the flux in the real beamline, and would be sensitive to large shifts in focusing parameters not covered by the focusing uncertainties, such as the 3 mm horn tilt recently discovered in the NuMI beamline, or degradation in target material (also seen in NuMI).

Two additional difficulties with the in situ option have emerged through preliminary Monte Carlo simulations, and subsequent discussions:

- The radiological background coming from the horns, particularly if the spectrometer is placed in between Horn B and and Horn C, is not negligible compared to the charged pion flux we are trying to measure. While still small - of the order of 1 count per 53 r.f. bucket, in a fine grained silicon strip detector, this background can not be ignored, as we still do not have a quantitative understanding of what will come out of the downstream end of the target support and from the wall of the chase. Any attempts at shielding the spectrometer from the walls of the chase is tricky, as it would require thick ( one foot) piece of clean steel be inserted in chase just downstream of the Horn B or C.

- Shielding steel, completely unnecessary and unwanted in the normal intensity mode, could also become the source of secondaries. More importantly, the material in the yoke and pole tips of the small ( 10 cm by 20 cm) aperture permanent magnet inside the spectrometer will create very significant background in the downstream section of the silicon tracker. In the ex situ case, we would use a much larger, conventional magnet, such the old Jolly Green Giant or Rosie magnet installed at the Meson West beam line. This background would be present at the edge of the 60 cm aperture radius, where the particle flux from the target/horn is much reduced.

For the ex situ option, numerous beamlines (Old KTev Hall, MIPP beam line, old NM-Center..) exist at Fermilab and could be refurbished to host the target, horns, and spectrometer. However, the cost of duplicating the horn power supply must be be factored in. Again, there would be no design costs, as this would a replica of the horn power supply for the LBNF beam. The cost of the capacitors, transformers, etc, has been estimated to be 4.5 $M, including a 30% contingency.

The impact on the operational schedule is quite different for the ex situ and in situ options. For the in situ option, we estimate spectrometer running would require roughly 6% of LBNF running time. The ex situ case would have a negligible impact on LBNF protons on target.

## Conclusion

Given the difficulties of the in situ option, and the fact that the primary purpose of the in situ option would be to indentify catastrophic problems with the focusing system, the proponents of the spectrometer currently believe the best option to be installation of the full spectrometer in a ex situ configuration, provided it is accompanied by a program of work to ensure that focusing uncertainties are as small as possible and very well quantified. Ideally this would include a simplified detector, such as a sheet of silicon sensors in situ. Such a detector would mitigate many of the disadvantages of the in situ option, such as the need for low intensity running and a complex support module for the spectrometer, but would be able to identify and help diagnose signficant alignment issues. An identical detector could be installed in the ex situ replica, providing a quantitative validation that the ex situ measurement is valid for the the actual beam.

## References


[1] R. Acciarri *et al.* [DUNE Collaboration], arXiv:1512.06148 [physics.ins-det].

[2] L. Fields. "A Priori Flux Uncertainties", talk at September 2016 DUNE Collaboration Meeting. https://indico.fnal.gov/contributionDisplay.py?contribId=67&confId=10613.

[3] C. Adams *et al.* [LBNE Collaboration], arXiv:1307.7335 [hep-ex].